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Effects of frying parameters on physical changes of tapioca chips during deep-fat frying

Running title: Deep-fat frying of tapioca chips.

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Summary

The interrelationships of the effects of frying time, oil temperature, and initial moisture content on moisture loss, oil absorption, and linear expansion of a tapioca starch chip half-product during deep-fat frying have been studied. Both oil absorption and linear expansion were affected, in different ways, by moisture loss. Oil absorption was essentially a quantitative water replacement process. On the other hand, linear expansion occurred as a result of rapid vaporization of water in the initial stages of frying, but reached a plateau before maximum moisture loss due probably to a transformation of the product from an expandable rubbery state to a rigid glassy state. Critical frying times, temperatures, and initial moisture contents, below which

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virtually no physical change occurred, were observed. The optimum set of frying parameters for maximum linear expansion appears to be a frying time of 40 s, an oil temperature of 200°C, and an initial moisture content of 15% (dry basis).

Keywords

Half-products, crackers, starch, linear expansion.

Introduction

Half-products have been defined as special food formulations that, upon immersion in hot frying oil, rapidly expand into a low-density, ready-to-eat, porous, and crisp product (Matz, 1984). These half-products, also known as intermediates, are usually produced by gelatinization of a starchy dough which is then shaped into different forms (usually thin chips) and dried to a horny consistency. One such product is *keropok* (or cracker) which is a popular snack food in Malaysia (Yu, 1993). Apart from the two essential components (i.e. starch and water), other ingredients (such as fish or other types of seafood) are usually added to produce different types of crackers.

Various aspects of *keropok* manufacture and formulation have been studied. Increased mechanization has led to greater productivity and products of superior quality (Yu *et al.*, 1981; Siaw *et al.*, 1985). Studies on formulation have involved primarily investigations on the effects of different types and amount of starch on the linear expansion and crispness of fish *keropok* (Yu, 1991a,b; 1993). The amylose: amylopectin ratio of the starches used appears to be a major factor affecting the expansion and texture of the fried end-product (Mohamed *et al.*, 1989; Haryadi, 1994). Insufficient water in the formulation causes incomplete gelatinization of the starch during steaming, resulting in a half-product that does not expand well on deep-fat frying. However, water in excess of the optimum level also limits expansion of *keropok* (Mohamed *et al.*, 1989).

Surprisingly, there is little information on how frying parameters (such as frying time, oil temperature, and the initial moisture content of the half-product) influence important physical changes (e.g. moisture loss, oil uptake, and volume or linear expansion) that occur during deep-fat frying of low-moisture half-products. Such physical changes have a direct bearing on the physical attributes and acceptability of the expanded end-products. For example, crispness, the most important quality attribute of *keropok*, is directly related to linear expansion, and only samples giving a linear expansion greater than 77% are considered acceptable (Siaw *et al.*, 1985; Yu, 1992). Since *keropok* is a deep-fat fried product, the amount of oil absorbed also becomes a major cost consideration and may have implications where health is concerned.

The interrelationships of the effects of these frying parameters, if any, on such physical changes have also yet to be studied. The objective of the present investigation, which is based on a simple binary gelatinized tapioca starch-water model system, was to obtain a more complete profile of any particular physical change derived from the interactions of some of the important frying parameters, so as to better understand the salient features of deep-fat frying of a low-moisture, heat-expandable half-product such as *keropok*. Tapioca starch was selected as it is one of the two major types of starch used commercially as the raw material for making *keropok*, the other being sago (Siaw *et al.*, 1985). Tapioca starch is also known to produce chips with excellent expansion properties (Yu, 1991b).

Materials and methods

Materials

Tapioca (*Manihot utilissima*) starch was obtained locally. A blended cooking oil containing refined palm olein, groundnut oil and sesame oil was used for deep-frying of the starch chips.

Preparation of tapioca chips

Tapioca starch was mixed with an equal weight of water and poured into trays to form a ca. 8 mm-thick layer of batter. After steaming at atmospheric pressure for 30 min, the tapioca gel obtained was cooled to room temperature by placing the trays in ice-water. The gel was cut into regular pieces measuring 20 x 12 cm, placed between two high-density polyethylene sheets to prevent sticking and passed through a pair of rollers. This was repeated using progressively narrower gaps between the rollers until a thickness of about 2 mm was achieved. The gel was then conditioned at $5^{\circ}C$ for 21 h, cut into 2.5 cm^2 pieces, and dried in an air-oven at $50^{\circ}C$ for 7 h. Dried pieces of 2 mm thickness were selected and stored in an air-tight container.

Moisture content adjustment

Tapioca chips were first dried over P_2O_5 for 5 days in evacuated vacuum desiccators. They were then equilibrated *in vacuo* over different saturated salt solutions in vacuum desiccators for 5 days at $25^{\circ}C$ to attain moisture contents in the range from 5-25% (dry basis). The moisture-adjusted chips were kept in air-tight bottles.

Deep-fat frying

One kg of blended cooking oil was heated in a thermostatically controlled oil bath until the desired temperature was achieved. The oil was preheated for about 2 h prior to frying and discarded after 6 h. One tapioca chip was fried at a time to avoid oil temperature fluctuation. After a fixed period, the fried chip was scooped out and laid on a Whatman No. 3 filter paper to remove surface oil and to cool. The expanded products so obtained were stored in air-tight bottles for further evaluation.

Determination of moisture loss

Moisture content was determined by drying duplicate 5 g ground samples in an air-oven at $105^{\circ}C$ to constant weight (ca. 5 h). The non-fat dry matter was assumed to remain the same during the frying process and the fat content in the chips before frying was considered to be negligible. % Moisture loss (ML) = $100(M_o - M_f)/M_o$, where M_o and M_f are the initial and final moisture contents (expressed as g/100 g non-fat dry matter), respectively.

Determination of oil absorption

Oil absorption was determined in triplicate following the method suggested by Mohamed *et al.* (1989). This involved weighing several pieces of chips before and after frying. % Oil absorption (OA) = $100(W_f - W_o)/W_o$, where W_o and W_f are the weights (g) of the dried chips before and after frying, respectively.

Measurement of linear expansion

Linear expansion was determined by measuring five lines drawn across each chip before and after frying (Yu *et al.*, 1981). Measurements were made on ten replicates. % Linear expansion (LE) = $100(L_f - L_o)/L_o$, where L_o and L_f are the lengths (cm) of the lines before and after frying, respectively.

Desorption isotherms of the half-product

The standardized static method of determination of sorption isotherms in foods, developed in the COST 90 project of the European Economic Community, was used with some modifications (Wolf *et al.*, 1984). Nine different saturated salt solutions with relative vapour pressure (RVP) in the range from 0.11-0.97 were prepared using analytical grade salts and distilled, deionized water. The RVP values for each salt and temperature were obtained from Greenspan (1977).

The tapioca chips were ground with a Glen Creston micro-hammer mill to pass through a sieve of 0.5 mm mesh diameter. About 50 mg of the finely ground samples, vacuum-dried at 40°C for 24 h, were filled into weighing bottles (40 x 20 mm) of known weight. The dry weight of the samples in each weighing bottle was obtained by further drying the samples *in vacuo* over P_2O_5 for at least two days in a vacuum desiccator. The samples were then humidified by exposure to a saturated water vapour environment in an evacuated vacuum desiccator for 24 h.

Humidified samples, in triplicate, were placed in 1-litre air-tight Kilner jars above known saturated salt solutions. At high relative vapour pressures (≥0.70), crystalline thymol was employed to prevent microbial spoilage of the sample. The hygrostats were sealed and placed in a thermostatted incubator maintained at the required temperatures (25°, 35° and 45°C). Samples were weighed periodically until an "equilibrium" or quasi-equilibrium state was attained. The precision of the weight measurement was ± 0.01 mg. The calculated "equilibrium" moisture contents were expressed as g H_2O/100 g dry matter.

Results and Discussion

Moisture loss

Tapioca chips with a moisture content of 9.5% (dry basis) were used to study the interactive effects of frying time

(t) and frying oil temperature (T) on moisture loss (ML) during deep-fat frying and to select a suitable frying time for subsequent experiments. The results are shown in Fig. 1a.

At frying temperatures lower than 160^{o}C, there was virtually no moisture loss even though t was extended to a full minute. This was visually confirmed by the absence of bubbling when the chips were immersed in the frying oil. The chips remained submerged as their density was apparently higher than that of the oil. However, at $T \geq 160^{o}$C, a considerable amount of moisture was lost in the first 40 s of immersion, beyond which there was little further change. Under such conditions, intense bubbling occurred over the entire surface of the chip at the beginning of frying as water was rapidly vaporized with the chips becoming less dense in the process, thus enabling them to float to the surface of the oil. The intensity of bubbling decreased progressively as frying continued. The loss of moisture thus exhibited a typical drying profile which is also commonly observed in deep-fat frying of high-moisture products such as potato slices (Gamble *et al.*, 1987; Rice & Gamble, 1989) and French fries (Kozempel *et al.*, 1991).

A characteristic feature of the frying process is that, at any particular T above 160^{o}C, a critical frying time (t_{cr}), at which drastic moisture loss was initiated, was clearly evident. The t_{cr} values generally decreased with increasing T, which is to be expected since the rate of heat transfer is a function of temperature.

Further experiments were conducted using a frying time of 40 s since moisture loss had more or less levelled off at this point. Fig. 1b shows the interrelationships of the effects of frying temperature (*T*) and initial moisture content (*M*) on *ML* of tapioca chips deep-fat fried for a fixed period of 40 s. Little or no moisture loss was evident when the frying temperature was below a certain critical frying temperature (T_{cr}) at any particular *M*. A drastic increase in *ML* occurred only when T_{cr} was exceeded. As shown in Fig. 2, T_{cr} decreased from ca. 190° to 130°C as the initial moisture content was increased from 5 - 15%. Further increases in *M* to 25% did not cause any further reduction in T_{cr}. Similarly, a critical initial moisture content (M_{cr}), below which negligible moisture loss occurred, was observed at frying temperatures below 160°C. At any particular *M*, *ML* increased rapidly with increasing *T* above T_{cr} until a plateau was reached. *ML* was generally greater for chips at higher *M* at any particular *T*.

As mentioned earlier, the deep-fat frying process approximates to a drying or moisture removal process (Blumenthal, 1991), despite the complexities introduced by simultaneous oil absorption and structural changes. It is known that the heat of desorption (ΔH_{des}) or the energy required for moisture removal, which can be calculated from desorption data using the Clausius-Clapeyron equation (Gevaudan *et al.*, 1989), becomes progressively higher when the moisture content is lowered, indicating the need for increasing amounts of energy to remove the progressively smaller amounts of water remaining in the material being dried.

According to Labuza (1968), in addition to the heat of desorption, the latent heat of vaporization of water (2256 J/g) must be added to obtain the total heat of drying (Q_d). Fig. 2 gives the Q_d - moisture content relationship of the tapioca chips studied, with ΔH_{des} being derived from the desorption isotherms shown in Figure 3. It is clear that Q_d remained more or less constant as the moisture content was reduced from 28% to 20%, but increased drastically as M dropped below 15 g/100 g dry matter. It is also evident from Fig. 2 that the T_{cr} - M relationship closely parallels that of the Q_d - M relationship, both curves exhibiting a prominent inflexion at ca. 15% moisture. This is to be expected since the total amount of heat energy transferred from the oil to the chips is determined by the oil temperature, other conditions remaining constant. At M lower than this inflection point, a greater amount of heat energy, determined by T_{cr}, had to be supplied to overcome the higher heat of water binding in order to initiate moisture removal.

Oil absorption

The effects of t, T, and M on oil absorption (*OA*) by tapioca chips during deep-fat frying are shown in Fig. 4. Oil uptake appeared to parallel moisture loss under the same frying conditions. The amount of oil absorbed was insignificant when moisture loss was minor. More or less the same t_{cr}, T_{cr} and M_{cr} values were observed where both *ML* and *OA* were concerned.

As shown in Fig. 5, a highly significant correlation ($r = 0.935^{**}$) was found between *OA* and *ML* of tapioca chips, irrespective of the frying conditions employed. The linear relationship displayed a slope close to unity, indicating that oil uptake during deep-fat frying of tapioca chips is essentially a water replacement process (Pinthus *et al.*, 1993). Gamble *et al.* (1987) have also reported that the moisture-oil content relationship was linear for fried potato slices ($r = 0.998$) regardless of the frying temperature used. Reddy & Das (1993) noted that the oil content of potato chips at any time was independent of oil temperature and thickness of the slice, but was closely related to the moisture present and obtained a correlation coefficient of 0.98 between oil and moisture contents. Means of lowering the oil uptake ratio (U_R), defined by Pinthus *et al.* (1993) as oil uptake (g)/water removed (g), should be explored so as to achieve high moisture loss (and concomitantly, high volume expansion) but low oil uptake since this would be beneficial in terms of both cost and health.

Linear expansion

Fig. 6 shows the linear expansion (*LE*) profiles of deep-fat fried tapioca chips as influenced by *t*, *T*, and *M*. A comparison of Figs 1a and 6a shows that *LE* was initiated at the same time as *ML*, i.e. the t_{cr} values were the same for both these physical changes under the same frying conditions, suggesting that rapid vaporization of water is the primary driving force for half-product expansion and failure to achieve this caused the chips to remain unexpanded.

However, linear expansion reached a maximum level (LE_{max}) after a much shorter frying time than *ML*. The effect was also observed when a higher *T* was employed. For example, the maximum *LE* at 220°C was reached after frying for 20 s but it took about 40 s when *T* was lowered to 190°C.

As shown in Fig. 6b, tapioca chips with high *M* (> 15%) began to expand when *T* was raised above 130°C (= T_{cr}) as was similarly observed for moisture loss. Also, *LE* was initiated at a much higher temperature when *M* was lowered. When Figs 1b and 6b are compared, it can be seen that, at any particular *M*, maximum *LE* was attained at a lower frying temperature than maximum *ML*. A moisture loss of about 20-50%, depending on *M*, was found to be sufficient for maximum *LE* to take place. The initial moisture content of the half-product has a profound influence on both the magnitude of LE_{max} and the frying temperature at which this was achieved.

The effects noted above may be explained using a polymer science approach as advocated by Slade & Levine (1991). According to Colonna *et al.* (1989), expansion of half-products is due to rapid water vaporization inside the amorphous starch matrix, which is in a rubbery state, as the frying temperature is above the glass transition temperature (T_g). At the beginning of frying, the tapioca chips would be in a rubbery state enabling expansion to take place. As frying progresses, moisture loss, which equates to a decrease in plasticizer content (Slade and Levine, 1991), would rapidly elevate the T_g of the chips to a point where the chips would no longer be in a rubbery state but a glassy one. At this stage, further expansion, if any, would be minimal even though water would continue to be vaporized. This explains why LE_{max} was attained well before ML_{max} was recorded.

When chips with high *M* (> 15%) were fried at very high temperatures (T > 230^{o}C) for the same duration of time, *LE* was lower than that obtained at relatively lower frying temperatures (Fig. 6b). This could be due to the fact that water was being lost at too fast a rate at such high frying temperatures. This would cause the T_g to rise rapidly and the material to turn glassy at an earlier stage, thereby limiting expansion. The decrease in *LE* could also be attributed to an acceleration of chemical (e.g. non-enzymic browning) and physical changes (e.g. collapse of structure) as a result of the extremely high frying temperatures employed.

At any particular *T*, linear expansion increased with increasing *M*, but levelled off when *M* exceeded 15% (Fig. 6b). This relatively large expansion at high *M* may seem desirable but the structural strength of the resulting crisps was observed to be poor, being far too friable when compared with crisps prepared from chips with a lower *M*. In determining the optimum *M*, the storage stability of the half-product has also to be taken into account. Tapioca chips with *M* > 15% would have a water activity above 0.7 and be more prone to microbial spoilage resulting from mould growth.

Based on linear expansion, the optimum combination of the three frying parameters studied appear to be a *T* of 200^{o}C, a *t* of 40 s, and an *M* of 15%. Under such conditions, a highly expanded crisp end-product, with virtually no evidence of browning (an undesirable trait where *keropok* is concerned), was obtained.

Concluding remarks

The present study underlines the significance of the interactive effects of frying parameters on changes in physical properties of low-moisture expanded half-products during deep-fat frying. The importance of comparing the effects of treatments (e.g. different ingredients) on linear expansion using the optimal set of frying conditions relevant to each treatment is worth emphasizing. The practice of using a fixed set of frying conditions, which is not necessarily optimal for all treatments, in comparative studies of this nature may lead to erroneous conclusions regarding the relative effectiveness of the treatments studied. Furthermore, since the initial moisture content of a half-product is a particularly sensitive factor affecting physical changes during deep-fat frying, its lack of control in several of these studies can be considered a serious oversight which may invalidate any conclusion drawn.

Acknowledgments

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Legends to Figures

Fig. 1. Moisture loss (*ML*) profile of deep-fat fried tapioca chips as influenced by (a) frying temperature (*T*) and time (*t*) at a constant initial moisture content (*M*) of 9.5%, and (b) *T* and *M* at a constant *t* of 40 s.

Fig. 2. Effects of initial moisture content (*M*) of tapioca chips on the total heat of drying (Q_d, o) and the critical frying temperature (T_{cr}, △).

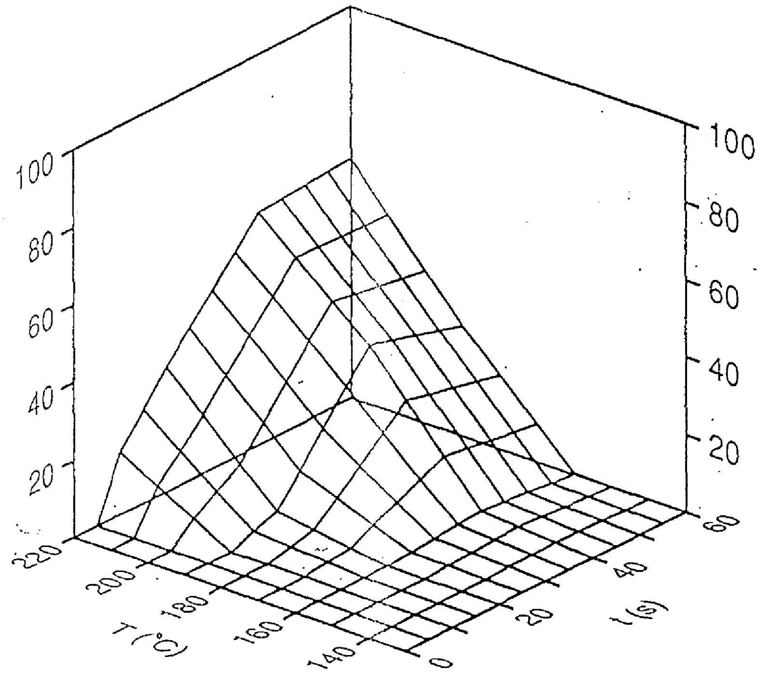
Fig. 3. Water desorption isotherms of tapioca chips at 25° (o), 35° (▲) and 45°C (□).

Fig. 4. Oil absorption (*OA*) profile of deep-fat fried tapioca chips as influenced by (a) frying temperature (*T*) and time (*t*) at a constant initial moisture content (*M*) of 9.5%, and (b) *T* and *M* at a constant *t* of 40 s.

Fig. 5. Relationship between oil absorption (*OA*) and moisture loss (*ML*) during deep-fat frying of tapioca chips.

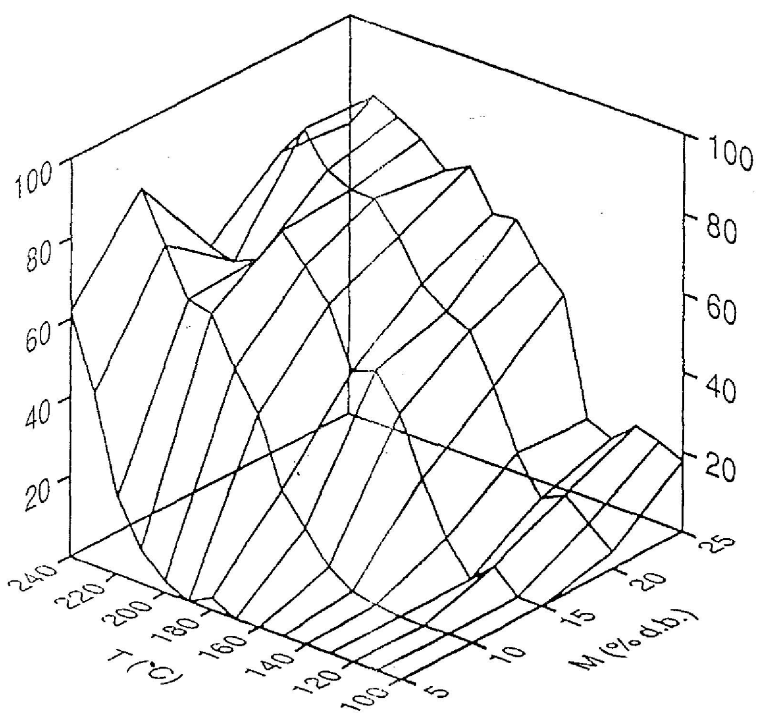
Fig. 6. Linear expansion (*LE*) profile of deep-fat fried tapioca chips as influenced by (a) frying temperature (*T*) and time (*t*) at a constant initial moisture content (*M*) of 9.5%, and (b) *T* and *M* at a constant *t* of 40 s.

(a)



100
80
60
40
20
220
200
180
160
140
T (°C)
0
20
40
60
t (s)
% ML

(b)



100
80
60
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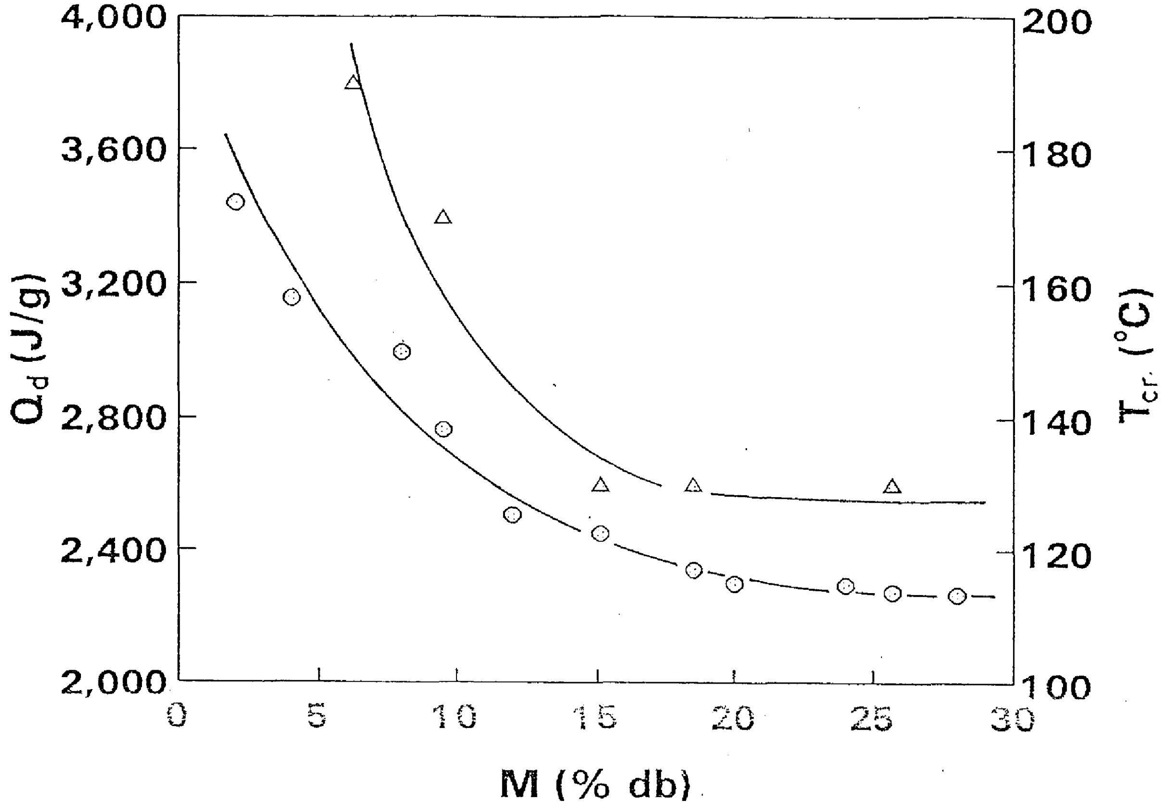
20
240
220
200
180
160
140
120
100
T (°C)
5
10
15
20
25
M (% d.b.)
% ML


Q_d (J/g)
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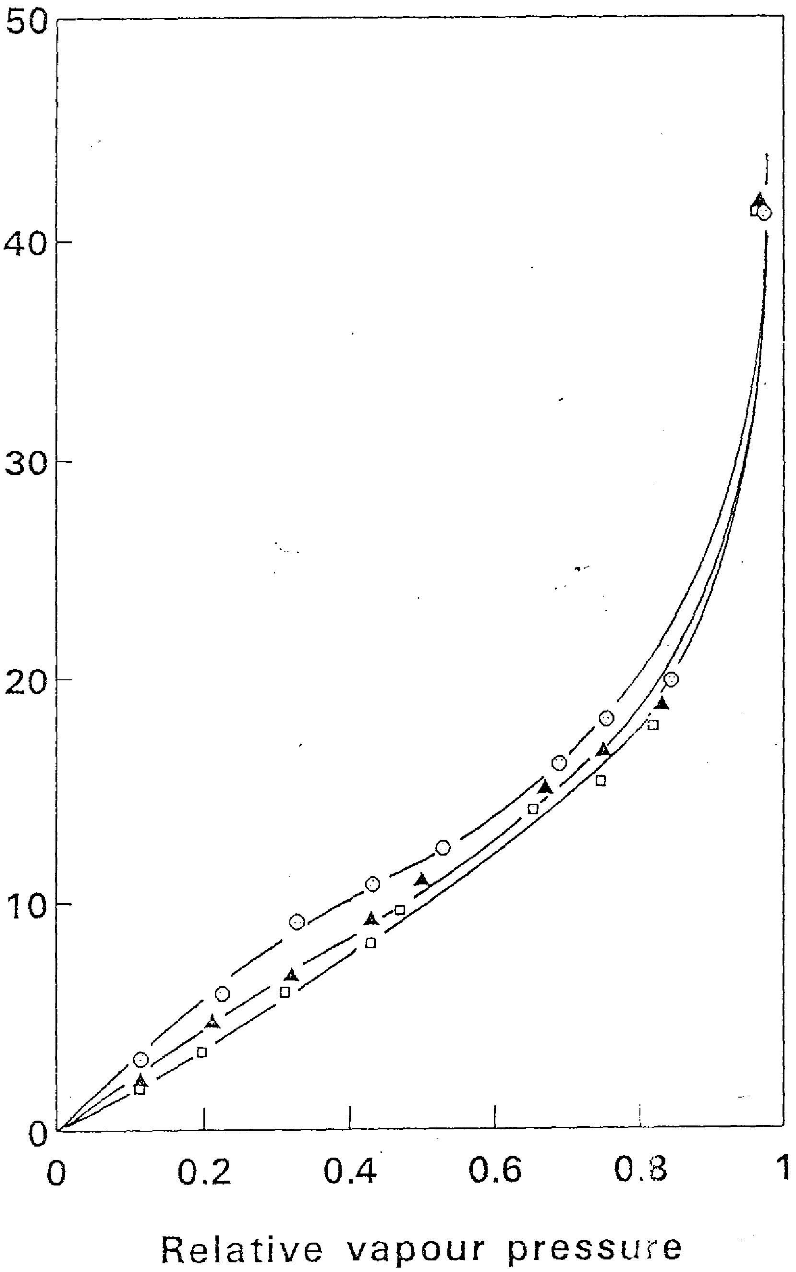
3,200
2,800
2,400
2,000
0
5
10
15
20
25
30
M (% db)
200
180
160
140
120
100
T_cr. (°C)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40
30
20
10
0
0
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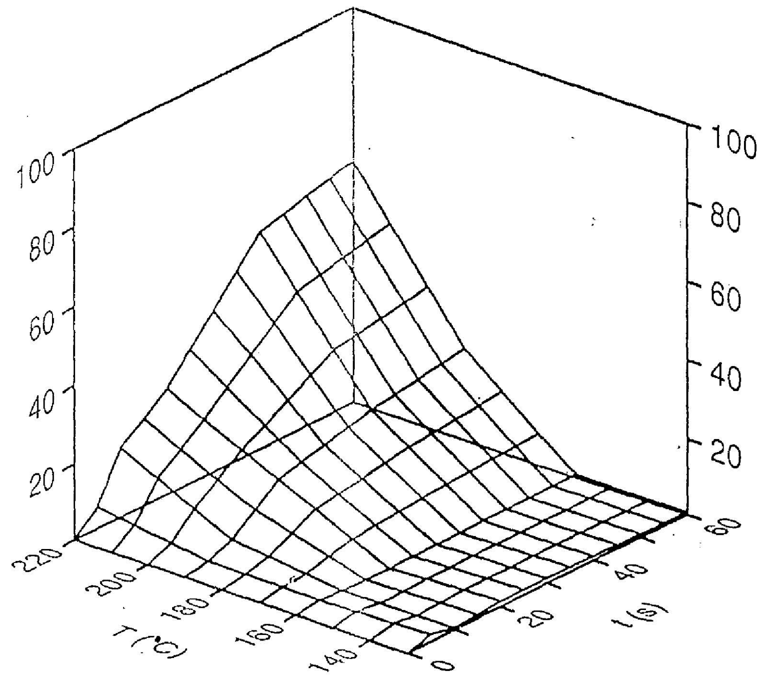
0.4
0.6
0.8
1
Relative vapour pressure

(a)



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T (°C)
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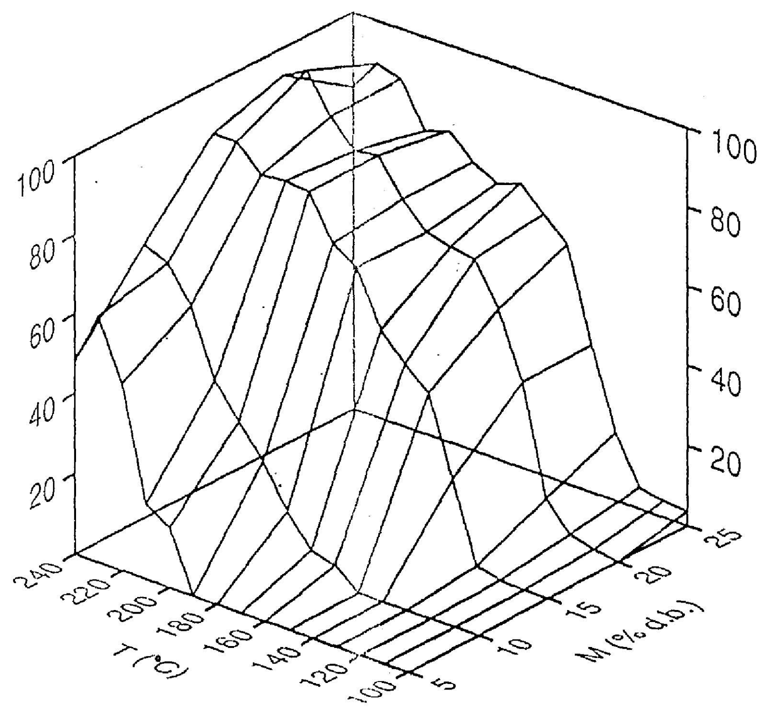
t (s)
100
80
60
40
20
% OA

(b)



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T (°C)
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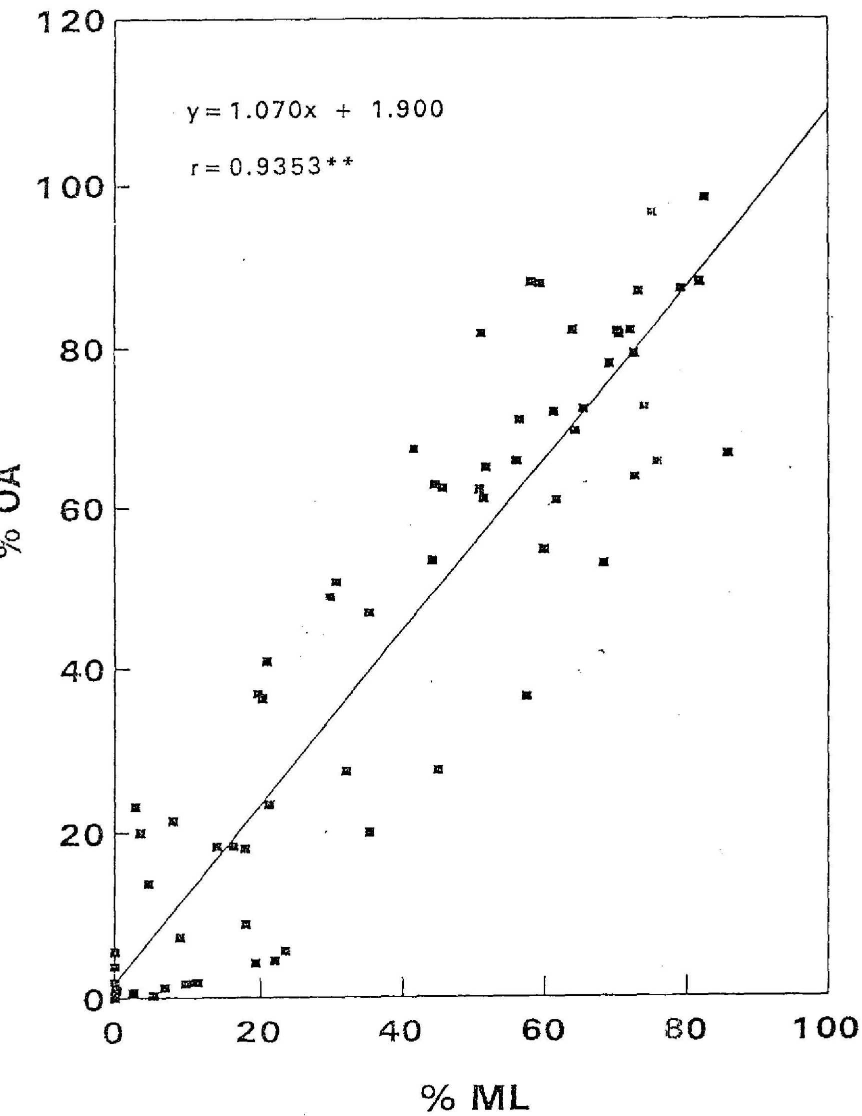
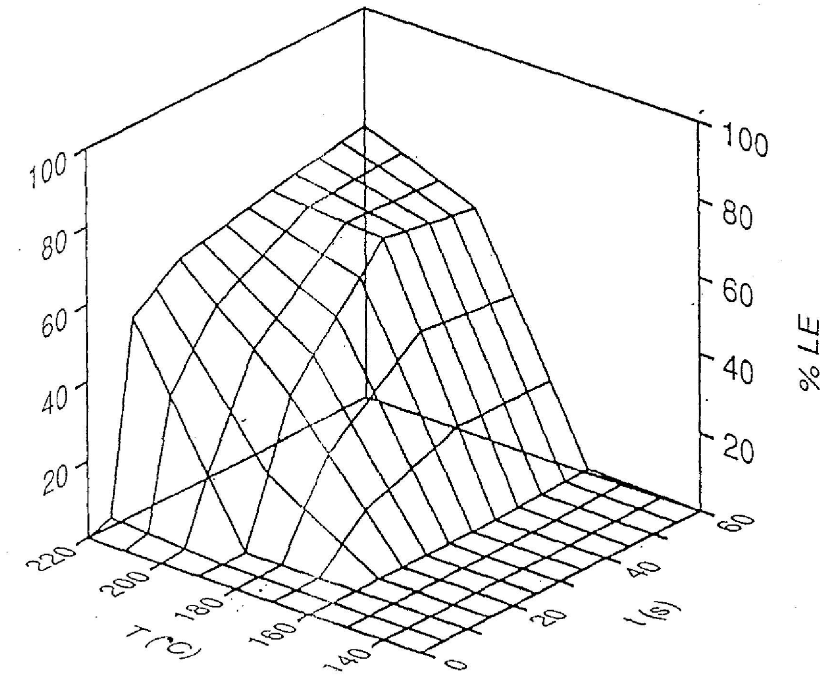
25
M (% d.b.)
100
80
60
40
20
% OA



y = 1.070x + 1.900
r = 0.9353**
120
100
80
60
40
20
0
0
20
40
60
80
100
% UA
% ML

(a)



100
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T (°C)
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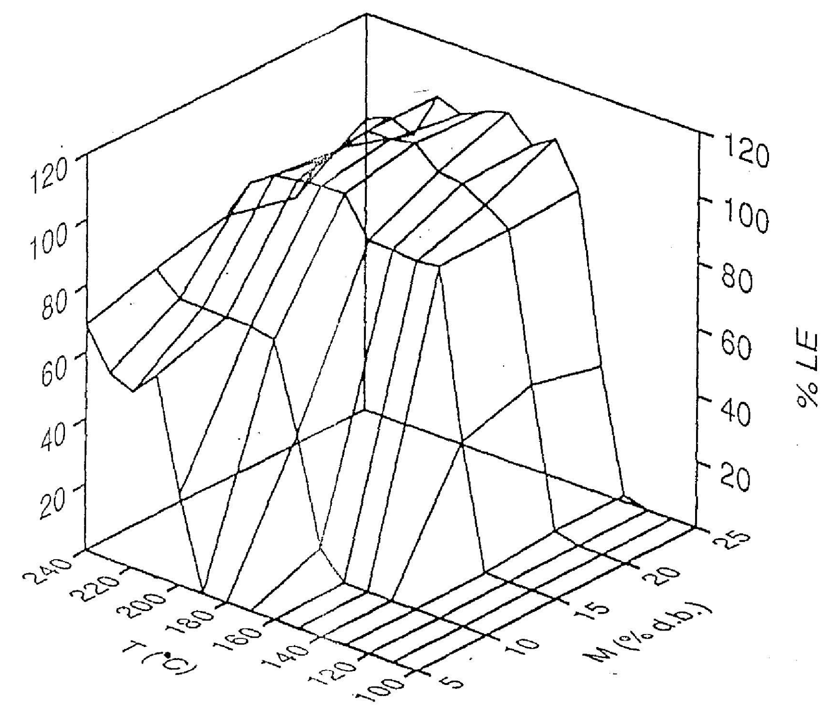
40
60
t (s)
% LE

(b)



120
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100
T (°C)
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20
25
M (% d.b.)
% LE